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Environmental impacts of decommissioning nuclear power plants: methodical challenges, case study, and implications

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Abstract
Purpose Environmental impacts of the decommissioning of nuclear power plants are brought into focus by the nuclear phase-out in Germany and a worldwide growing number of decommissioning projects. So far, life cycle assessments of decommissioning nuclear power plants have been conducted very rarely or are based on rather uncertain assumptions. Against this background, environmental impacts of the ongoing decommissioning of the nuclear power plant in Lubmin (KGR), Germany are examined. Methodological aspects like transferability to other decommissioning projects as well as influence of assumptions about the lifespan of a power plant are discussed.
Methods A life cycle assessment of the decommissioning according to ISO 14040/44 is conducted. The decommissioning of one power plant (of the assessed KGR) is chosen as functional unit. The system boundaries include removal and demolition of plant components and buildings as well as decontamination, conditioning, interim storage, and final repository of low-level and interim-level nuclear waste together with disposal and recycling of conventional waste. Interim storage and final repository of high-level nuclear waste such as fuel rods are excluded from the system boundaries as they are assigned to the use phase of the plant. Primary data was obtained from the plant decommissioning firm (Energiewerke Nord GmbH, EWN) in Lubmin. The GaBi database was used to model background processes. Environmental impacts are estimated using the CML2001 methodology.
Results and discussion Environmental impacts are mainly caused by on-site energetic demands of component removal and peripheral tasks. Further significant impacts are caused by the handling, storage, and final repository of low-level and intermediate-level nuclear waste. Recycling conventional, nonradioactive metallic waste has the potential to unburden the process in a significant scale, depending on recycling rates.
Conclusions The dismantling of nuclear power plants shows a relevant environmental impact. Regarding the environmental impacts per kilowatt-hour assumptions concerning the plant' lifespan are a crucial factor. Comparing the result from this study to recent datasets for nuclear power poses the question if LCA datasets represent environmental burdens of nuclear power accurately.

The transferability of LCA results to other studies using one parameter for scaling is problematic and needs further research.

Keywords Decommissioning of a nuclear power plant · Environmental impacts · Life cycle assessment · Nuclear phase-out

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1 Introduction

Nuclear power is a controversially discussed power source and the debate about it has been additionally fueled by the tragic incident in Fukushima in 2011. Relatively low carbon emissions in the use phase—especially when compared to fossil energy sources—are confronted with unpredictable risks and the unsolved problem of the final disposal of nuclear

waste. In Germany, the post-Fukushima debate led to the political decision of a complete nuclear phase-out by 2022, bringing along a growing number of decommissioning projects. Also globally, a growing number of decommissioning projects can be observed, raising the question of the resulting environmental impacts, an issue that has so far been treated only superficially in most life cycle assessment (LCA) studies dealing with nuclear power.

While in LCA studies of renewable energy sources, a lot of attention is paid to the construction and dismantling phases (see, e.g., Nugent and Sovacool 2013; Zimmermann 2013; Fthenakis and Kim 2011); in most studies on the environmental impacts of nuclear power just like in studies of fossil energy sources, the focus usually is on assessing the use phase. Proper assessments of the plants decommissioning have been conducted very rarely and are often based on rather uncertain, nontransparent or even unsound assumptions. Ergo, it remains unclear in how far the lengthy process of decommissioning contributes to the life cycle-wide environmental impacts and if it has been over- or underestimated in previous studies and LCA datasets.

Against this background, an LCA study of the decommissioning of the former nuclear power plant in Greifswald-Lubmin, Germany is presented in this paper. In addition, a brief review of the state of science is performed and the transferability of the results to other decommissioning projects is assessed.

2 LCA and emission data of decommissioning nuclear power plants: state of science

In general, it can be said that the environmental impacts of energy production technologies are well investigated. Numerous studies have been published for various types of energy production technologies and energy carriers, including oil, hard-coal, and lignite (e.g., Gagnon et al. 2002; Odeh and Cockerill 2008a; Pehnt and Henkel 2009), gas (e.g., Odeh and Cockerill 2008b), renewables like sun and wind (e.g., Nugent and Sovacool 2013; Zimmermann 2013; Zimmermann and Gößling-Reisemann 2013; Fthenakis and Kim 2011), as well as nuclear power (e.g., Lenzen 2008; Beerten et al. 2009; Sovacool 2008).

For assessing the state of science regarding published LCA data on nuclear power, a review of literature has been carried out. In the first part of this review, life cycle-wide LCA data are considered, while in a second part, data referring specifically to the plant's end-of-life are looked at separately. Scientific publications (Lenzen 2008; Beerten et al. 2009; Hennings 2006; Marheineke et al. 2000; Sovacool 2008) including three review studies (Lenzen 2008; Beerten et al. 2009; Sovacool 2008) have been considered in this review. References considered in both reviews have been taken into account only once. In addition, LCA data from LCA databases (PE 2013; UBA 2013; SCLCI 2013) have been considered. Since the greenhouse gas (GHG) emissions per kilowatt-hour (kWh) measured in grams of CO_2 equivalents (CO_2 eq.) per kWh, i.e., the carbon footprint, are the only indicator reported in all the considered sources, in the following we focus on this indicator.

An overview of life cycle-wide GHG emission data of nuclear energy is given in Figs. 1 and 2. From these figures, it can be seen that the data (CO_2 eq. emissions per kWh) vary quite a bit. While the majority of studies and LCA datasets indicate GHG emissions of up to 30 g CO_2 eq./kWh, there is still a significant share of publications and LCA datasets indicating higher emissions of up to 120 g CO_2 eq./kWh.

To some extent, these variations are caused by methodological differences and differing system boundaries. Even though the GHG emission data in all of the considered studies are supposed to be representative for the entire life cycle including construction and commissioning of the plant, uranium extraction and enrichment, nuclear waste disposal as well as the decommissioning of the plant, only in about two thirds of the studies (e.g., Lenzen 2008; Sovacool 2008) the life cycle is in fact considered in its entirety. In the remaining studies, the stages of decommissioning, intermediate and long-term storage of intermediate and high level (ILW/HLW) that are together referred to as "backend" are not considered which, of course, results in differences in the reported GHG emission data.

Furthermore, reasons for the diversity in the reported GHG emissions per kWh also include actual technological differences, e.g., differences in the reactor type which determines the amount of nuclear waste generated which then influences

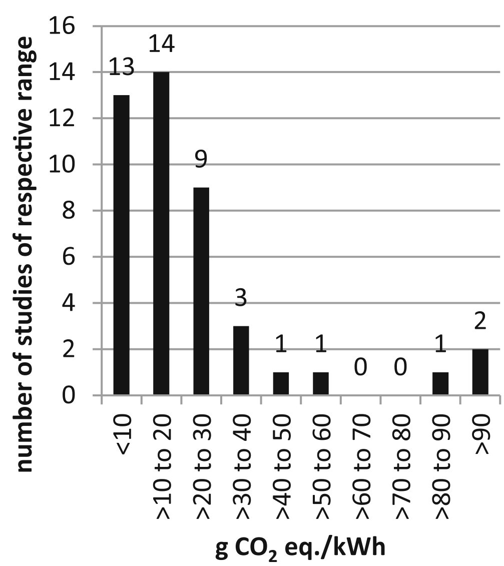

Fig. 1 CO_2 eq. emissions of nuclear power from different publications (histogram) (Lenzen 2008; Beerten et al. 2009; Hennings 2006; Marheineke et al. 2000)

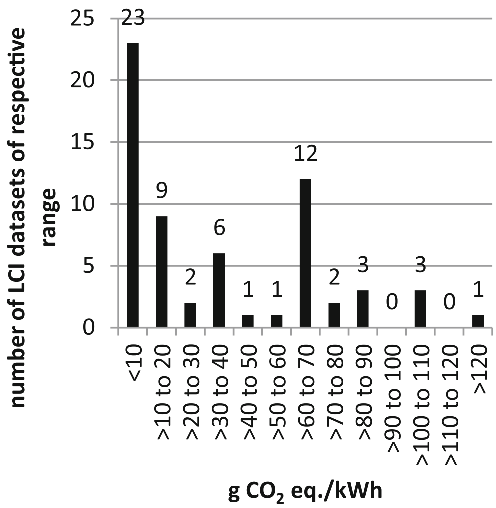

Fig. 2 CO_2 eq. emissions of nuclear power from different *LCIA datasets* (histogram) (GaBi 5.0, ecoinvent 2.2, ProBas) (PE 2013; UBA 2013; SCLCI 2013)

the volume that needs to be decontaminated, conditioned, and deposed.

Another important aspect is the assumptions made regarding the plant's operating time. The operating time determines the energy output which is the denominator for calculating the carbon footprint. Therefore, differing assumptions on the operating time and the resulting total energy output result in significant differences in the GHG emissions per kWh. Thus, it can make sense to take a separate look at the environmental impacts of each life cycle phase of a nuclear power plant.

Regarding the decommissioning phase, it has to be noted that in all considered studies and dataset documentations, the decommissioning phase is described rather sketchy. This is probably caused by insufficient knowledge base, i.e., a so far very small number of conducted decommissioning projects and a corresponding even lower number of LCA studies regarding these decommissioning projects.

Confronted with this weak data basis, many studies scale the environmental impacts of the plant's construction to the end-of-life phase based on rather intransparent scaling factors to estimate the environmental impacts of dismantling. Due to high environmental and safety standards regarding the treatment of nuclear residues which results in a manifold increased effort compared to the construction phase, this approach has to be questioned. While building and commissioning a nuclear power plant is comparable to the respective process of a fossil power plant, decommissioning involves a much higher effort due to the requirements of decontamination and safe storage of nuclear residues which come along with higher energy and material demands compared to the shutdown of a conventional power plant.

Data regarding GHG emissions resulting from the *decommissioning phase* of a nuclear power plant is relatively scarce. In Fig. 3, data collected from different studies is presented.

The GHG emissions, again, vary quite a bit. While most studies show CO_2 eq. emissions between 0.17 and 1.3 g CO_2 eq./kWh, two studies show emissions higher than 30 g CO_2 eq./kWh.

To the authors' knowledge, the only LCA study of decommissioning a nuclear power plant that is actually based on the decommissioning process of a real-life reactor has been conducted by Wallbridge et al. (2012). Here, the former nuclear power plant in Trawsfynydd, Wales is assessed. The 390 MW plant is currently decommissioned; the site will be fully cleared at the end of the current century since a safe enclosure was chosen as decommissioning strategy. During the whole decommissioning process, 241,000 t CO_2 equivalents which means 3.5 g CO_2 eq./kWh are estimated to be emitted (Wallbridge et al. 2012).

3 Method and general approach

The presented LCA study has been conducted according to ISO 14040/14044 (DIN 2009a, 2009b). The CML2001 methodology (Guinée and Lindeijer 2002) has been used for the impact assessment. The LCA model was built in GaBi 6.0; PE datasets have been used to model the background system (PE 2013). The goal of the study was to analyze the environmental impacts of the decommissioning process of the former nuclear power plant in Lubmin (Greifswald) in Germany (Kernkraftwerk Greifswald, KGR). Although most LCA studies of energy technologies use the amount of generated electric energy (kWh) as functional unit, the whole decommissioning process (i.e., "decommissioning of one nuclear power plant (KGR)") has been chosen as functional unit in this study. In contrast to fossil electricity generation, emissions from the generation of nuclear energy can mainly be allocated to the frontend (i.e., uranium milling and enrichment) and backend (i.e., conditioning and disposal of nuclear waste) phases, while only a minor

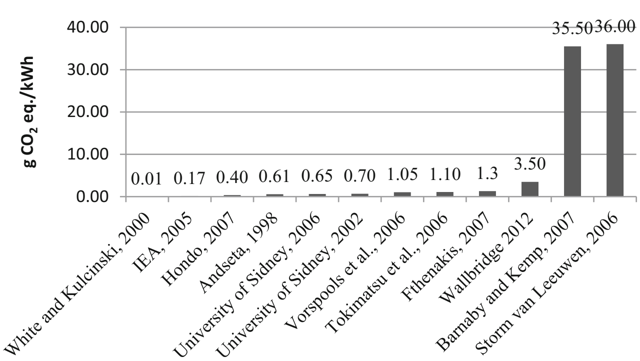

Fig. 3 Overview of results from studies assessing a.o. the decommissioning phase of the nuclear life cycle

share of the environmental impacts results from the use phase (Sovacool 2008). Referring the environmental impacts of commissioning or decommissioning to the electricity output which depends on the lifespan (i.e., on the use phase) may distort results because there is no linear causality between lifespan and the environmental impact of decommissioning. Therefore, "decommissioning of one nuclear power plant (KGR)" was chosen as functional unit. Additionally, the only known comparable LCA study regarding the decommissioning of a real-life nuclear power plant (Wallbridge et al. 2012) also uses a whole decommissioning project as functional unit; so a direct comparison of absolute results is achievable. However, to allow a comparison with other previous studies (see, e.g., Fig. 3), the emissions per kWh are assessed additionally to the described functional unit.

4 System description and life cycle inventory

The KGR started operation in 1973 and was shut down after the German reunification in 1990. During this time, the five pressurized water reactors with an electric output of 1,760 MW generated 146,466 GWh of electricity. Infrastructure on the plant area was built for eight reactors since original plans intended the installation of three more reactors. The public owned company Energiewerke Nord (EWN) is responsible for the ongoing decommissioning activities that have started in 1995 (Sterner et al. 1995). The chosen decommissioning strategy is a crossover between an immediate dismantling and a safe enclosure. Executing an immediate dismantling means removing all activated and decontaminated components as well as facilities after the post-shutdown phase. Safe enclosure is another strategy to decommission a nuclear power plant and includes the containment of the plant buildings and components and to let them decay naturally. After a period of time that can take up to 60 or 70 years, building and component removal is the last step of the decommissioning process. The crossover strategy conducted in Greifswald means that the removal of radioactive components like reactor pressure vessels and steam generators is the first step within the project. Deconstruction and demolition of buildings and periphery structures will be executed after a few decades (EWN 2013b). Unlike other nuclear power plants to be decommissioned, an intermediate storage facility (interim storage north, ISN) was built on the plant area to facilitate intermediate storage of radioactive waste. In addition to waste arising from the decommissioning of KGR facilities, ISN is also used to store radioactive components and waste from the near-located, decommissioned nuclear power plant in Rheinsberg (KKR). In the former "warm workshop" that was used as a maintenance workshop during operation time, now, contaminated components are decontaminated using mechanical, chemical, and electrochemical techniques. Several other buildings located on the area are exemplarily used for radioactivity measurements and classification, temporary storage of waste to be decontaminated, or as space for periphery systems.

Figure 4 gives an overview of system boundaries, excluded process steps, and data sources. The conducted LCA begins after the removal of spent fuel rods. Waste treatment (i.e., interim and final storage) of fuel rods is excluded from the study since the study focuses on the end-of-life (EOL) or decommissioning stage, respectively, and fuel rods representing the primary energy carrier in nuclear power generation are assigned to the use phase. Transport activities have been considered in this study but are not separately shown in the chart since they are modeled as subprocesses within the primary processes. Land remediation had to be excluded due to lack of data. However, a recent study indicates that this process has only a minor contribution to the total result (Wallbridge et al. 2012). In the following, data sources (Section 4.1) and the different process steps as shown in the Fig. 4 (Section 4.2) are described in more detail.

4.1 Data sources

A brief overview of data suppliers according to the respective process steps is given in Fig. 4. Main data suppliers were the

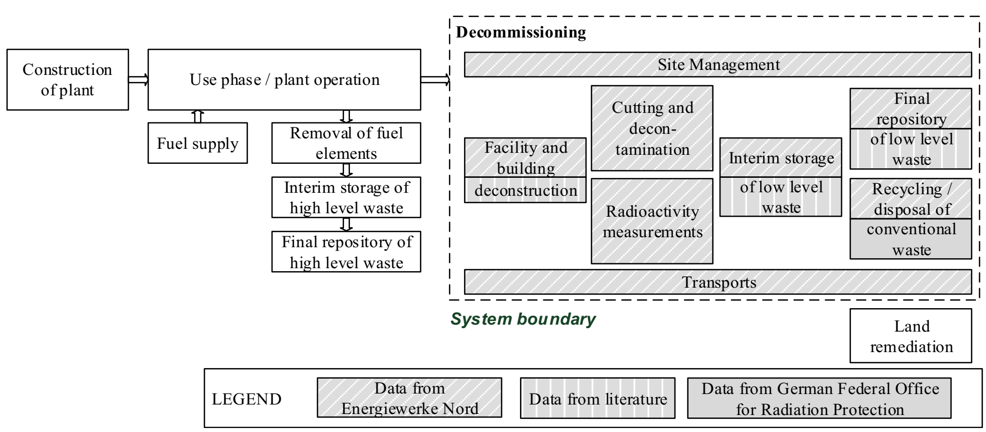

Fig. 4 System boundaries and data sources of present study

EWN and the German Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, BfS). Only little process information had to be taken from literature (Dones et al. 2009). EWN provided technical reports from 1995 to 2011 containing information about yearly waste amounts as well as types and numbers of interim storage containers (EWN 2013a). Energy reports from 2010 and 2011 contained information about the on-site buildings energy demand in Greifswald from 2006 to 2011. These figures were scaled back to the beginning of decommissioning activities (1995) and up to the predicted finish of decommissioning in 2020 (EWN 2013b). This scaling method was validated in discussions with experts from EWN. In addition, details on applied processes and applied technologies have been obtained from EWN experts.

Final repository of radioactive waste lies in the responsibility of the BfS. The BfS provided information about energy demands of the commissioning phase of the final repository "Konrad." The final repository is going to be commissioned in 2019; further information on it is given in Section 4.2.5.

4.2 LCI input data

Table 1 gives an overview of the aggregated material and energy flows that result from decommissioning of the KGR and its related processes as shown in Fig. 4, respectively. Specific information concerning the process steps are described in the following paragraphs.

4.2.1 Facility and building deconstruction

Component dismantling and building demolition includes the disassembly of components as well as the final demolition of buildings. It begins with removal of components for electricity generation coming from the primary and the secondary circuit

Table 1 Overview of accounted LCI data

Process step	Major energy flows	Major material flows
Facility and building deconstruction	Electricity: 714 GWh Heat (gas): 1,344 GWh Process steam (gas): 304 GWh Diesel: 8,363,726 l	
Radioactivity measurements	Electricity: 16 GWh Heat (gas): 155 GWh	
Cutting and decontamination	Electricity: 76 GWh Heat (gas): 303 GWh Process steam (gas): 54 GWh	Oxygen: 466,759 Nm^3 (cutting) Acetylene: 13,103 Nm^3 (cutting) Hydrogen: 32,780 Nm^3 (cutting) Argon: 32,780 Nm^3 (cutting) Phosphoric acid: 2,140 t (decontamination) Oxalic acid: 487 t (decontamination) Steel granulate: 937 t (decontamination) Water: 20,815 t (decontamination)
Interim storage of LLW	Electricity: 131 GWh Process steam (gas): 399 GWh Diesel: 603,501 l	Concrete: 171,298 t (building) Steel: 9,254 t (building and drums) Lead: 2,350 t (drums)
Final repository of LLW	Electricity: 64 GWh Diesel: 645,409 l Heating oil: 109,052 GJ Heating gas: 21,310 GJ	Concrete: 909,322 t (construction/containers) Steel: 2,889 t (construction and containers)
Recycling/disposal of conventional waste		Residual steel: 184,057 t (100 % RR) Residual copper: 5,531 t (95 % RR) Residual aluminum: 1,123 t (90 % RR) Residual lead: 506 t (70 % RR) Residual concrete: 1,523,282 t (89 % RR) Debris: 264,294 t Wood: 1,738 t Conventional waste: 16,436 t Hazardous waste: 6,256 t
Site management	Electricity: 349 GWh Heat (gas): 721 GWh Process steam (gas): 135 GWh	
Overall transports	Rail: 12,246,587 tkm (drums/containers for interim storage/final repository) Truck: 418,626,739 tkm (Recycling/disposal of conventional waste)	

(PC/SC). The PC contains all components that are directly exposed to radiation during operation—e.g., reactor pressure vessels, steam generators, and pressurizers—whereas the SC is separated from the PC by a heat exchanger. The SC contains all components known from conventional electricity generation, e.g., turbines, generators, and cooling facilities. Every component used in the PC is potentially contaminated. Components from the SC can be decommissioned and recycled conventionally. The main buildings on the plant area are the turbine house containing the SC components and the reactor buildings containing PC components. The turbine house is currently as well as in the future used as a factory building for several companies until its final demolition that is likely going to take place at the end of the century. The reactor buildings are going to be demolished after PC components have been removed. For both, reactor buildings and the turbine house, currently there is no fixed date for demolition.

The component dismantling is linked to high energetic demands in terms of heat and electricity demands that are going to occur until the last component is removed from the respective reactor building. The reactor buildings have to be heated during the whole year because of the high isolation of thick concrete walls and harsh climatic conditions at the Baltic Sea coast (EWN 2013b). Electricity and process steam is necessary for dismantling activities through machinery. Thermal energy demand in terms of heat and process steam is met by an on-site gas turbine. While the facility deconstruction is a highly complex and safety-relevant issue, final demolition of buildings can be conducted like the demolition of a conventional building with heavy machinery once radioactivity levels lies under safety values. The total concrete mass of KGR adds up to 1.7 million tons (Motzko and Löhr 2010). A diesel demand of 4.82 l/t concrete to be demolished was assumed (Lünser 1999).

4.2.2 Radioactivity measurements

Within the disassembly and deconstruction of the nuclear power plant, all scrap, components, and other waste coming from facility and building deconstruction that are potentially radioactive have to be measured in order to classify them as radioactive or conventional waste. These radioactivity measurements are conducted in the former warehouse. Thus, no special infrastructure except the clearance measurement devices had to be installed. Therefore, only energy use in the form of electricity and gas for heating had to be accounted for; the respective data has been taken from EWN (2013a). The total amount of material of potential radioactivity before measurements is about 566,419 t. Thereof, it was measured that 471,190 t were not contaminated leaving 95,229 t for decontamination (see Section 4.2.3).

4.2.3 Cutting and decontamination

Components that are classified as radioactive have to be decontaminated and sometimes cut in order to establish their safe handling in the following processes.

Depending on the material and the type of contamination, different routes of decontamination are possible. Besides decontamination by chemical, electrochemical, and mechanical processing, as described below, some material is stored in the interim storage for natural decay until conventional recycling can be conducted taking into account the regulations of the German Federal Atomic Energy Act. In addition, some material is transferred to the final underground repository without any decontamination. Chemical, electrochemical, and mechanical decontamination as well as thermal cutting of bulky waste components are conducted in the former so-called "warm workshop" which is located on the site and was used for maintenance and repair activities during the use phase of the plant.

Materials used for the different cutting techniques of radioactive facilities are oxygen, acetylene, hydrogen, and argon. Depending on the chosen decontamination method, equipment runs with water, phosphorous acid, oxalic acid, or steel granulate. Data regarding material and energy consumption in cutting and decontamination has been obtained from EWN (2013a) and Rohde (2008).

A total mass of 95,229 t has to be treated in the "warm workshop" (Sterner et al. 1995). According to Rohde (2008), from 1997 to 2007, a total mass of 3,660 t of material has been decontaminated from which 22 % have been decontaminated using water, 14 % using steel granulate, 36 % using phosphorous acid, and 18 % using oxalic acid. These figures were scaled up to the decontamination demand of the total decommissioning process (95,229 t). The total demand of decontamination material can be taken from Table 1. The same scaling has been conducted for material demand for the variant cutting of components.

4.2.4 Interim storage of low-level waste/intermediate-level waste

Waste from decontamination that has to be stored intermediately before final repository or that will be recycled conventionally after natural decay is stored in the interim storage north (ISN). The ISN started operation on the plant area in 1998 and is now used for storage of low-level waste (LLW)/intermediate-level waste (ILW). Depending on how long the commissioning of the final repository Endlager Konrad takes, the duration of intermediate storage is not finally predictable.

Construction as well as operation of the ISN has been considered in the study. Building materials were scaled from architectural drawings and verified with EWN employees

(EWN 2013c). Since no data concerning energy consumption for commissioning of ISN was available, data from Dones et al. (2009) was used and scaled based on the storage volume.

Lastly, energy demands of the ISN operation phase taken from EWN (2013a) were accounted for. The total amount of stored waste before transportation to the final repository is assumed to be 7,405 m^3 based on data from EWN (2011, 2012).

Regarding the ISN's operation, materials used for interim storage containers were accounted for. The storage of contaminated waste takes place in several different canisters. These canisters used for interim—and some also for final—storage mostly consist of steel and partly of concrete. A small number also has a further lead film. The material demand of containers used in the ISN as well as their absolute numbers can be found in Table 2 (Pfeiffer et al. 2011).

The aggregated energy and material flows of the interim storage of LLW/ILW are shown in Table 1.

4.2.5 Final repository of LLW/ILW

Waste that has undergone decontamination treatment and/or natural decay in ISN and still shows a level of radioactivity above the radiation limits of the German Federal Atomic Energy Act has to be stored in a final repository. Final repository of LLW/ILW took place in the Final Repository Morsleben (ERAM) and from 2019 will take place in the Final Repository Konrad (EKON). ERAM is a former salt deposit that was rebuilt to store radioactive waste from 1971 onwards, and in 1998, it was decided to safely seal it off from the biosphere. Meanwhile, EKON has been built in a former iron ore mine near Salzgitter, Germany. While the construction of ERAM required deepening of new vertical chutes and underground chambers, construction of EKON only requires creating new chambers (BfS 2012b).

The total volume of nuclear residues from German nuclear power plants is assumed to sum up to 280,000 m^3 so that most of the storage capacity is going to be used for waste from energy generation. Moreover, some percent of waste to be stored come from research reactors of medical appliances (BfS 2012b). The planned storage capacity of EKON is 303,000 m^3 of nuclear waste.

The lifecycle of a final repository for LLW/ILW covers construction, storage, and filling. After the total mass of radioactive waste has been stored underground, the caverns are filled with concrete. A further monitoring of the repository is not intended at the moment. Therefore, modeling of both of the final repositories for LLW/ILW contain construction phase, use phase, and filling of underground infrastructure.

Materials for construction and backfill as well as energy demands for construction and operation were accounted as shown in Table 1. Modeling of both of the final repositories is based on information from BfS and literature (BfS 2012a; Dones et al. 2009; Hoffmeyer et al. 1996) since further primary data was not available.

ERAM Energy demands for the construction of ERAM were taken from Hoffmeyer et al. (1996) and include exploration, operation of shaft winding equipment, vehicles, and aboveground facilities. Since no primary data for material demands was available, a scaling of the figures of Dones et al. (2009) was conducted. The volume of waste to be stored in the final repository was chosen as the basis for scaling. While the final repository in Dones et al. (2009) is 100,000 m^3, storage volume of ERAM is 35,820 m^3. The energy demands for operation of ERAM in terms of electricity, diesel, oil, and gas were taken from Hoffmeyer et al. (1996). After storing LLW/ILW in the final repository, a total mass of 4,000,000 m^3 concrete is filled into the chambers and vertical chutes (BMUB 2012a).

During operation, 35,820 m^3 of LLW/ILW was stored in ERAM, whereas LLW/ILW from KGR only adds up to 3,425 m^3 (EWN 2013a). The total material and energy demands of ERAM were accounted with a share of 9.3 % to the stored waste of KGR. Total energetic and material demands for the lifecycle of ERAM—scaled down to the amount of waste from KGR—can be taken from Table 3.

EKON The lifecycle and therefore the modeling approach for EKON in large parts equal the ones of ERAM. The modeling approach for construction implies a scale up of energetic

Table 2 Containers for interim storage

Container type	Material and process demand	Total amount in ISN
200 l steel barrel	Steel: 41.8 kg Welding seam: 0.89 m	20,223
280 l steel barrel	Steel: 76 kg Welding seam: 1.03 m	59
400 l steel barrel	Steel: 60 kg Welding seam: 1.1 m	24
580 l barrel	Steel: 204.25 kg Lead: 545.75 kg Welding seam: 1.2 m	4,307

Table 3 Material and energetic demand of ERAM

	Energetic demand	Material demand
Construction	Electricity: 12 GWh Diesel: 94,886 l	Steel: 41.99 t
Use phase/storage ERAM	Electricity: 34 GWh Diesel: 134,258 l Oil: 99,303 GJ Gas: 19,405 GJ	
Filling		Concrete: 372,102 m^3/893,054 t

demands that were available for 2011 and 2012 in terms of electricity, diesel, gas, and oil for heating (BfS 2012a, 2013c). The construction phase is currently assumed to last 12 years from 2008 to 2019 (Borlein 2009). Therefore, the average energetic demand was scaled up for this timeframe.

The approach for modeling material demand for constructing of EKON follows the same approach as the one for modeling EKON. Since EKON is going to contain 303,000 m^3 of LLW/ILW, the scaling factor in comparison to Dones et al. (2009) is 3.03. The energetic demand for the operation of EKON uses the average demand of the construction phase and is scaled up to 40 years which is the planned storage timeframe (Borlein 2009). Oppositional assumptions—implying energetic demand is going to vary from demands for construction—cannot actually be made (BfS 2013c). Filling of EKON in contrast to filling of ERAM does not include filling both vertical chutes and chambers with concrete, but only chambers. Therefore, the total concrete demand for filling EKON equals 202,000 m^3 (BfS 2012b). The vertical chutes and other cavities are filled with debris that was assumed to come from the construction of the repository and therefore was not considered.

A total volume of 303,000 m^3 of LLW/ILW is planned to be stored in EKON from all German nuclear facilities. A storage volume of 7,405 m^3 is assigned for upcoming waste from KGR so that total energetic and material demands were accounted for with a share of 2.44 %.

Table 4 shows the total energetic and material demands accounted for the lifecycle of EKON scaled down to the relative share of waste from KGR.

Containers for final repository Material demands for the production of final repository containers (taken from Pfeiffer et al. (2011) as shown in Table 5) are included in the life cycle model. Containers for final repository mainly consist of steel and/or concrete. Additionally, some of the containers and barrels used for intermediate storage are directly used for final repository without further packaging.

Table 4 Material and energetic demand of EKON

	Energetic demand	Material demand
Construction	Electricity: 4.05 GWh DIESEL: 96,061 l Heat: 2,250 GJ Gas: 440 GJ	Steel: 90.35 t
Use phase/storage ERAM	Electricity: 13.5 GWh Diesel: 320,204 l Oil: 7,499 GJ Gas: 1,465 GJ	
Filling		Concrete: 4,936 m^3/11,675 t

4.2.6 Recycling/disposal of conventional waste

In case waste from deconstruction and demolition, from radioactivity measurements, decontamination, or interim storage is not under the scope of the German Federal Atomic Energy Act, it can be recycled and led back into conventional material cycles or disposed conventionally.

This process step only covers conventional wastes. Data of conventional waste was taken from EWN (2013a). Material flows supplied to conventional recycling or disposal are concrete and debris, metallic resources (steel, lead, aluminum, and copper), whereas steel comes mainly from building reinforcement and copper mainly from electric components and cables. The total input of material supplied to conventional recycling or disposal can be taken from the respective section of Table 1.

For conventional recycling of metals, credits were given. They equal the difference of the energy demand of their raw production in comparison to their recycling energy demand (Grimes et al. 2008) considering recycling rates and process losses (Zimmermann 2013; PE 2013).

Concrete was assumed to be recycled completely based on information from EWN (2013b). Recycling of concrete was modeled as the material substitutes aggregate used for concrete production. Debris and consumer waste is deposited to an inert/conventional waste landfill while hazardous waste is transported to a hazardous waste deposit.

4.2.7 Site management

Site management comprises all buildings and facilities that in former times were not directly connected to electricity generation. They are now for example used as administrative buildings, hazardous substances warehouses, (hot) water processing facilities, or security buildings. For modeling energy demand of those periphery buildings, heat, electricity, and process steam demands were taken from energy reports and scaled up to their respective lifetime (EWN 2013a; EWN 2013b).

4.2.8 Transports

Transport processes take place within the processes “interim storage of LLW/ILW,” “final repository of LLW/ILW,” and “recycling/disposal of conventional waste.” They were modeled as a part of their superordinate process and are not shown separately in the LCI/LCIA results.

Relevant transports for modeling the systems are mainly connected to handling of radioactive and conventional waste. This contains transport of intermediate/final storage containers to the plant as well as transport of the respective containers to the final repository. Transports of containers from their production site in Lower Saxony waste to the

Table 5 Containers for final repository

Container type	Material and process demand	Total amount in EKON/ERAM
200 l steel barrel (only used for final repository in ERAM)	Steel: 41.8 kg Welding seam: 0.89 m	15,149
Konrad IV steel container	Steel: 2,200 kg Welding seam: 25 m	472
Konrad IV steel container with concrete inlay	Steel: 2,200 kg Welding seam: 25 m Concrete: 7,800 kg	473
Concrete container	Concrete: 2,700 kg	338
Cast container	Steel (casted): 5,880 kg	5

plant—and later to the final repository—add up to 800 km per container. Radioactive waste transport is carried out by train (EWN 2013b).

The second process step containing transports is the handling of conventional waste. All types of conventional waste are transported to a landfill/recycling plant that is located 209 km from the plant by truck (EWN 2013b).

5 LCIA and sensitivity analysis

Environmental impacts were calculated using CML2001. With regard to recycling rates, two alternative scenarios have been assessed. Scenario 1 considers 100 % of residual material as waste to be landfilled. The second scenario, "100 % recycling," assumes that scrap metals is recycled completely (100 % recycling rate). Still, metal losses from recycling processes have been considered in the second scenario (according to information from Zimmermann 2013, PE 2013, and Grimes et al. 2008).

As EWN intends to provide 100 % of residual material for recycling, results are discussed referring to the scenario "100 % recycling." Absolute results are given in Table 6. While credits from recycling unburden the results of AP, EP, GWP100, and POCP between 13 and 72 %, ADP even has a positive value due to high amounts of secondary metals from decommissioning. Recycling of concrete does not have a notable impact.

An overview of the relative contributions of the subprocesses is given in Fig. 5. It can be seen that most environmental impacts result from facility and building deconstruction. Most of these impacts in turn, result from dismantling of components. As the decommissioning of a nuclear power plant is a long-term project, energy demands from various buildings sum up to remarkably high electricity and thermal energy demands (see Table 1).

Radioactivity measurements only demand a small amount of energy and therefore do not contribute significantly to overall results.

The reason for the high share of interim storage of LLW regarding the abiotic depletion potential is the high amount of lead used for the production of radioactivity absorbing barrels. In comparison to other metals and substances which have a high share in the material demand (for example steel), lead has a much higher characterization factor (lead: 0.0135 kg Sb. eq. steel: 8.43E-8 Sb. eq.) (Guinée and Lindeijer 2002).

Site management has a notable share in total environmental impacts coming from energy demands. Considering the plant infrastructure that was built for eight reactors and large parts of this infrastructure is still, e.g., as hazardous waste storages or for (hot) water supply explains this high share.

Environmental impacts from transport processes are directly accounted to the respective superordinate process stage like "final repository of LLW/ILW" or "recycling/disposal of

Table 6 Results of LCIA for non-recycling and recycling scenario

Environmental impact	Without recycling	100 % Recycling	Relative credit	Relative emissions
ADP	6.74E+0 t Sb. eq.	−3.10E+1 t Sb. eq.	−559 %	−0.21 mg Sb. eq. kWh
AP	2.63E+3 t SO_2 eq.	1.54E+3 t SO_2 eq.	−41 %	10,5 mg SO_2 eq./kWh
EP	3.38E+2 t PO_4 eq.	2.92E+2 t PO_4 eq.	−13 %	1,9 mg PO_4 eq./kWh
GWP100	1.89E+6 t CO_2 eq.	1.65E+6 t CO_2 eq.	−13 %	11.27 g CO_2 eq./kWh
POCP	2.67E+2 t Ethene eq.	7.35E+1 t Ethene eq.	−72 %	0.50 mg Ethene eq./kWh

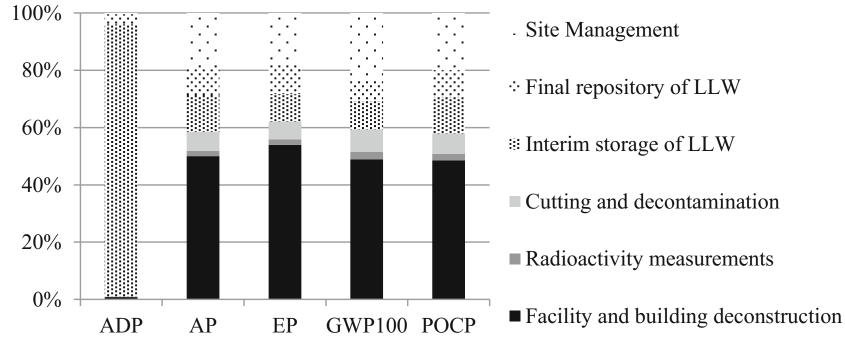

Fig. 5 Relative contributions of process steps to LCIA result

conventional waste.” However, they do not contribute to the relative results in a notable manner.

Sensitivity analyses were conducted regarding currently uncertain parameters. These include the duration of commissioning of final repository Konrad, the duration of on-site decommissioning activities, and the volume of low-level nuclear waste in the final repository Konrad.

The first parameter is the duration of the commissioning of final repository Konrad. Initially, it should have been ready for storage of nuclear residues in 2012. This first commissioning date was corrected to a renewed commissioning date in 2019 (Borlein 2009). Therefore, the commissioning duration was extended to another 5 years (up to 2024) in the sensitivity analysis.

Since the date of the finalization of on-site decommissioning activities in Greifswald cannot be clearly answered by now, the planned finishing date in 2020 was set to 2022 in the second conducted sensitivity analysis. Although the total activities necessary to conduct the decommissioning do not depend on the timeframe of the project, the duration was chosen as one parameter to vary because of the high thermal heating demand of the former reactor buildings (EWN 2013b). The KGR is located near the Eastern Sea and has climatic conditions that lead to the necessity to heat the buildings made of thick concrete walls (compare Section 4.2.1). The variation of the projects duration only implies change in the energy demand but no changes in demands for materials, i.e., for decontamination.

Up to now, the volume of radioactive waste that has to be stored in a final repository is only an estimated value. Therefore, this volume was varied from −10 to +10 % as a third parameter in the sensitivity analysis.

Varying the duration of on-site decommissioning activities showed that it is the only parameter with a significant influence on the overall result. While the variation of commissioning duration and storage volume for the final repository led only to minor changes, extending the duration of on-site decommissioning activities increased the results by 13.8 % as shown in Fig. 6.

6 Discussion

6.1 Comparison of results to other studies and LCA datasets

The total GHG emissions including credits for recycling or decommissioning of KGR amount to 1,651,265 t CO_2 eq. In reference to the generated power of 146,499 GWh during the operating time of KGR, the specific emissions amount to 11.27 g CO_2 eq./kWh.

Compared to the results of other studies, the present study implies several aspects to consider regarding the decommissioning phase of a nuclear power plant.

Emissions from decommissioning of KGR exceed the data for decommissioning nuclear power plants presented in other studies (see Fig. 3) and even exceeds the life cycle-wide emissions of various studies and datasets (see Figs. 1 and 2). The comparison to other datasets refers to all datasets covering nuclear power generation from the databases of GaBi, ecoinvent, and ProBas (PE 2013; SCLCI 2013; UBA 2013).

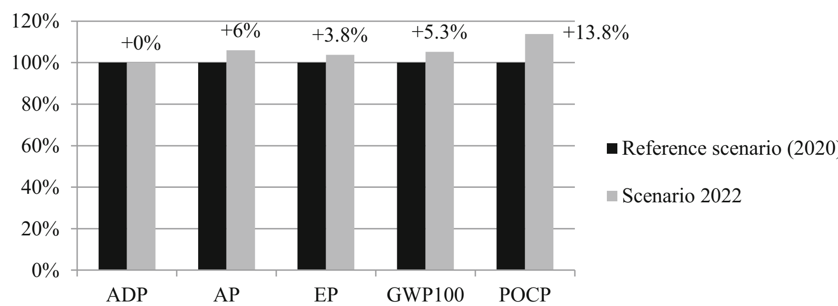

Fig. 6 Sensitivity analysis of decommissioning duration for presented impact categories

For example, in GaBi 6.0 datasets, life cycle emissions of GHG of nuclear electricity generation range from 4 to 15 g CO_2 eq./kWh. Considering that in this study emissions of 11.27 g CO_2 eq./kWh have been calculated only for the decommissioning phase, an underestimation of life cycle-wide emissions can be assumed.

6.2 Operation time

As mentioned before, most LCA studies of electricity generation use the electricity output as the functional unit. This may be appropriate analyzing technologies using fossil primary energy carriers since most emissions result from burning of energy carriers and therefore occur during operation. For electricity generation techniques that do not use fossil energy carriers like renewable energies or nuclear power, this methodical approach has the clear disadvantage that the lifespan of systems and facilities has an immense influence on the relative emissions.

In LCA datasets, life spans of nuclear power plants are widely assumed to be around 40 years. The reactors of the KGR had an average operating time of 14 years. This gap between assumed and actual operating time is not an exclusive exception. Especially in Germany where the last nuclear power plant will be shut down in 2022 due to the nuclear phase-out, life spans of nuclear power plants are varying strongly as shown in Fig. 7 and quite some of them will not reach a total lifespan of 40 years. The figure refers to the effective operational lifetime of already shut-down plants and the planned lifetime of the remaining plants to be shut down until 2022.

Knowing that most emissions result from deconstruction and interim/long-term storage of LLW/ILW implicates that there is no direct dependency of operation time and decommissioning-related emissions. In contrast to this, there is a very clear dependency between life span and electric output. This shows that the functional unit “kWh” has a high potential to distort relative results.

6.3 Scaling results

Given the lack of well-founded information on the environmental impact of the decommissioning of nuclear power plants and a growing number of decommissioning projects, the transferability of the results of this study to other plants needs to be investigated. Decommissioning a nuclear power plant is a highly complex and to some extent unique project that does not allow an undeliberate scaling of results to other power plants without proving a general transferability. The possibility of scaling results to other plants to be decommissioned in turn is an interesting research question for assessing the environmental impacts of decommissioning a whole reactor fleet. Especially in Germany where the nuclear phase-out will be conducted until 2022, transferring results from this study to decommissioning projects of other plants may help to understand the environmental burdens resulting from the duty to decommission these plants.

Scaling methods based on the nominal output, the number of reactors, and the amount of regular waste are discussed here. The compared parameters are waste amounts relative to the number of reactors and to the electric output (MW_{el}). They were chosen because of their correlation to the environmental impacts occurring during decommissioning. A higher reactor number or electric output leads to more waste due to a higher need for infrastructure such as reactor buildings, storage, and peripheral facilities. Knowing that the electric and thermal energy demand of a plants buildings and facilities during the decommissioning process has one of the highest shares of environmental impacts has been the basis for choosing these parameters.

Table 7 shows this comparison. It can be seen that absolute waste amounts of decommissioning KGR exceeds other ones by far as well as there is no clear correlation between the number of reactors/electric output and the waste amount. Thus, it shows the difficulties that occur trying to scale a project on the basis of reactor number or electric output. The large difference between the KGR and the other nuclear power plants in the last two columns can be explained by the fact that infrastructure and buildings were already built for the planned number of eight reactors, but the plant was shut down before the sixth reactor went into commercial operation. Adding the three planned reactors and the respective electric output to the values above leads to smaller differences in the comparison of KGR and the other plants.

For finding a correlation between waste amounts and environmental impacts, the total waste amount was set into proportion to the total CO_2 eq. emissions of the project. Taking into account these values from the present and the Welsh study shows a relatively wide range of results

Fig. 7 Operation time of German nuclear power plants referring to their effective and advised operation time according to German nuclear phaseout plans (BfS 2013a, BfS 2013b; Bundesgesetzblatt 2011)

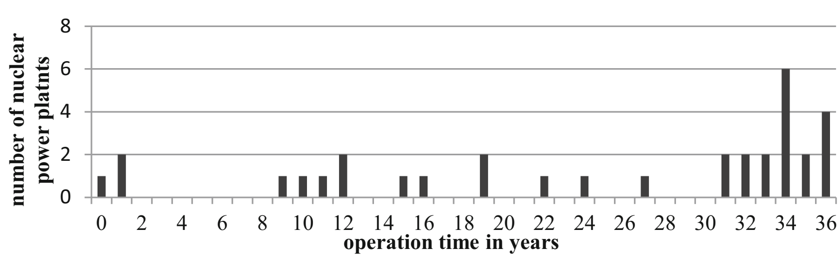

Table 7 Reactor number, electric output, and waste amount of several nuclear power plants

	Reactor type (number)	Output (MW_{el})	Waste (t)	Waste per MW (t/MW_{el})	Waste per reactor (t/reactor)
AKW Maine Yankee	PWR (1)	860	180,483	209.9	180,483
KTF	PWR (2)	390	203,500	521.8	101,750
Mülheim-Kärlich	PWR (1)	1,302	490,000	376.3	490,000
Nuclear power plant Stade	PWR (1)	630	330,000	523	330,000
KGR	PWR (4)	1,760	2,000,000	1,136	500,000

according to the formulas below. The values vary around 1 with a deviation of around 20 %.

$$\boldsymbol{KTF}: \frac{\boldsymbol{CO_2eq._{KTFi}}}{\boldsymbol{waste}\ [\boldsymbol{t}]_{\boldsymbol{KTF}}} = \frac{241,000\ \text{t}\ CO_2\text{eq.}}{203,500\ \text{t waste}} = 1.18$$

$$\boldsymbol{KGR}: \frac{\boldsymbol{CO_2eq._{KGR}}}{\boldsymbol{waste}\ (\boldsymbol{t})_{\boldsymbol{KGR}}} = \frac{1,651,265\ \text{t}\ CO_2\text{eq.}}{2,000,000\ \text{t waste}} = 0.825$$

It must be regarded that the Welsh study does not give credits for recycling. Recycling credits would lower the result in a significant way and lead to a proportion that would be nearer to the one of the LCA of decommissioning KGR.

The comparison of these values shows that there is further research needed to analyze if there is a clear correlation between waste amounts and total CO_2 eq. emissions of decommissioning nuclear power plants. Simple or even linear scaling effects can be excluded by having a look at different environmental impact categories. For example, conducting the above comparison for other environmental impact category like acidification or eutrophication potential leads to factors for KTF that are about three to five times higher than the ones for the KGR.

If research shows a clear correlation of these values, scaling up CO_2 eq. emissions according to the volume of waste could be a reasonable method to extrapolate the results of an independent study to a larger scale like a whole reactor fleet.

6.4 Conclusion and implications

Summing up the results, various conclusions can be drawn. The comparison of the results of this study to other LCA studies and datasets indicates that the nuclear power plant's EOL, i.e., its process of decommissioning, might not be considered appropriately in these data and additional uncertainties that need to be dealt with may result from using such data. Even though the transferability of the results of this study to other power plants remains to be an object for further research, the results indicate that that the approaches used to estimate the environmental impacts of the EOL of nuclear power plants (e.g., based on the environmental impacts of constructing the plant) are often inappropriate.

The influence of the lifespan of a power plant is often neglected. Especially for nuclear power plants, life spans may vary strongly depending on political, economic, or safety issues. Assuming a life span of 40 years and more, many dataset lifespan assumptions differ widely from actual figures (compare Fig. 7). This shows that comparing decommissioning projects by using the generated electricity output as functional unit is problematic. In consequence, transferring the results from one study to another or even generalize results like done in LCA datasets may lead to errors in large scale. However, the electric output is the only functional unit that is able to consider the total lifecycle of an energy technology breaking it down to a comparable figure.

One possibility to encounter this potential for miscalculation is to provide different lifespan parameters for one dataset during its creation regarding the commissioning and decommissioning phase. In this way, the commissioning and decommissioning phase could be better allocated to the total lifecycle. Environmental impacts that have a more linear correlation like emissions during the use phase of a plant would not be influenced by this method. Implementing this would help to allocate more realistic values per kWh.

The transferability of this implication to other energy generation techniques is an issue to discuss. Technologies which do not burn fossil fuels such as nuclear power or renewable energies show that a high share of environmental impacts depends on their production and the decommissioning phases. Taking into account that there are only little long-term empirical values for the life spans of wind power plants or PV modules makes it an interesting question if recent datasets for these techniques represent environmental impacts in a proper range. Many LCA datasets and studies for wind power or solar power plants assume a life span of 20 years without having a clear basis for this assumption. Nevertheless, the comparison of nuclear power and renewable energy carriers is at least difficult since the life span of a nuclear power plant is a highly political issue. Although there are no long-term experiences of life spans of renewable energy, it is possible to assume a fixed operation time that has only limiting parameters of technical nature.

An important aspect for further research is a deeper analysis of interim storage and final repository of high-level waste (HLW) coming from used fuel elements. Interim storage and final repository are likely to have notable impacts on total lifecycle emissions. Although these process steps are to be

allocated to the use phase and were therefore excluded from the present study, analyzing impacts from treatment and storage of HLW would facilitate assessing the total life cycle emissions of nuclear power.

An approach to assess environmental impacts from HLW storage would be a scaling method for interim storage as well as final repository. Interim storage is comparable to the storage of LLW/ILW except containers for storage that have to absorb higher radiations. Containers for HLW are stored in the ZLN in a separated area so that a simple allocation of ZLN material and energetic demands—for example based on the floor area needed for storage—could allow assessing intermediate storage.

Scaling final repository material and energy demands is more complex. There is no decision about a final repository for HLW in Germany currently, although the search for a potential final repository endures since 1973 (GNS n.d.). After filling a potential final repository for HLW, monitoring and documentation has to be conducted further on. For 500 years, is has to be guaranteed that the waste is retrievable (BMUB 2012b). The search for a repository as well as monitoring and retrievability of waste is likely to be connected with significant material and energetic demands.

Looking at the transferability to other decommissioning projects, a need for further research becomes obvious, as well. So far, besides this study, only one further study of a real-life decommissioning project of a nuclear power plant exists. To allow more general conclusions and an evaluation of the transferability of the results, a broader basis of studies is needed.

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